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Standard Model Explanations for the NuTeV Electroweak Measurements

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Abstract. The NuTeV Collaboration has measured the electroweak parameters $\sin^2\theta_W$ and ρ in neutrino-nucleon deep-inelastic scattering using a sign-selected beam. The nearly pure ν or $\bar{\nu}$ beams that result provide many of the cancellations of systematics associated with the Paschos-Wolfenstein relation. The extracted result for $\sin^2\theta_W(\text{on-shell}) = 1 - M_W^2/M_Z^2$ is three standard deviations from prediction. We discuss Standard Model explanations for the puzzle.

The NuTeV Collaboration has performed a simultaneous measurement of the weak mixing angle and $\rho = G_F(\text{neutral-currents})/G_F(\text{charged-currents})$ in neutrino-nucleon deep-inelastic scattering using a sign-selected beam and a modified Paschos-Wolfenstein relation.[1, 2] The result, $\sin^2\theta_W(\text{on}-\text{shell}) = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$ gives a W-mass three standard deviations from the Standard Model as shown in Fig. 1. The details of the experiment have been covered elsewhere.[2, 3] This contribution will focus on several papers which have attempted to explain the effect based on Standard Model processes and will show why we think none are adequate.

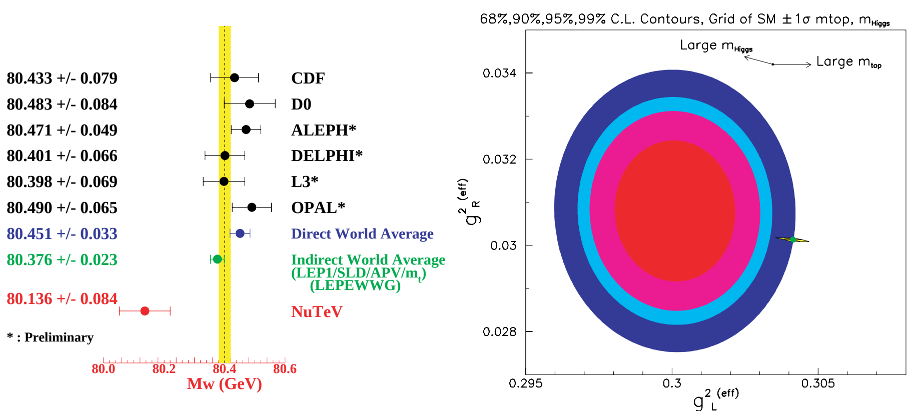

Figure 1. The left-hand plot shows the NuTeV result using a Standard Model $\sin^2\theta_W$. The right-hand side shows the effective couplings g_L and g_R. See [2] for details and radiative corrections for m_t, M_H .

Two of the explanations invoke effects in a kinematic region that has little effect on the result; hence we show the NuTeV kinematic regions in x and Q^2 in Fig. 2.

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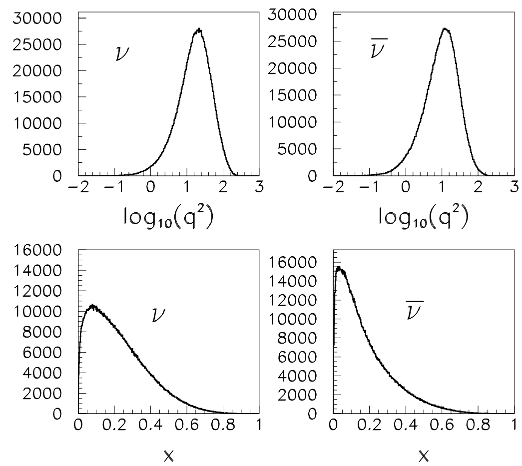

Figure 2. Monte Carlo predictions for the kinematic distributions of the NuTeV electroweak data sample.

1. Effect of an Asymmetric Strange Sea

This is the most sensible explanation, at least on the surface. Davidson *et al.* suggest an asymmetry in the strange sea could explain 0.0026 (1/2) of the discrepancy thereby "eliminating the anomaly." They quote a re-analysis of CDHS data that claims an effect of -1.75σ, $xs > x\bar{s}$ at high x.[4, 5] No weighting of this purported effect as a function of x was used in examining the NuTeV result.

First, let us examine the CDHS data on which this argument is based. The strange sea is determined through opposite-sign dimuon production: $\nu/\bar{\nu}_\mu$ scattering from $d, s \rightarrow \mu^\pm$ and $c \rightarrow \mu^\mp X$. This process is kinematically suppressed because of the charmed quark mass and requires relatively large hadronic energy. Table 1 shows the statistics of the CDHS and CCFR experiments. The analyses of Ref. [4, 5] rely solely on the CDHS data which are sorely lacking in relevant statistics. The CCFR data are in agreement with the NuTeV analysis. A combined CCFR/NuTeV analysis of the dimuon data has been published and the high x region specifically discussed.[6] The result was then combined with a functional form:

$$< s(x) > \; = \kappa \frac{\bar{u}(x) + \bar{d}(x)}{2} (1-x)^\alpha \tag{1}$$

$$< \bar{s}(x) > \; = \bar{\kappa} \frac{\bar{u}(x) + \bar{d}(x)}{2} (1-x)^{\bar{\alpha}} \tag{2}$$

obtaining central values for $\kappa, \bar{\kappa}, \alpha, \bar{\alpha}$ of 0.352, 0.405, -0.77, and -2.04 respectively; a full correlation matrix was determined.[7] The results were then combined with a functional form which includes all effects of the NuTeV analysis and detector simulation. We note from Fig. 2 that 73% (82%) of the $\nu(\bar{\nu})$ NuTeV data have $x < 0.3$. The results is *opposite* to that found by Ref. [4]:

$$< S > - < \bar{S} > \; = -0.0027 \pm 0.0013 \tag{3}$$

(where $< S > = \int s(x)\, dx$) with a corresponding *increase* in the NuTeV weak mixing angle of 0.0020 ± 0.0009. We interpret this result as consistent with zero. The explanation of the NuTeV result through an asymmetric strange sea, while not *a*

priori unreasonable, is only supported by an after-the-fact analysis of statistically poor data applied to the NuTeV analysis in the wrong kinematic region. The result from an internally consistent, high statistics determination gives, if anything, a larger discrepancy with the Standard Model. There is no experimental justification for an asymmetric strange sea as a Standard Model explanation. Finally, Loinaz *et al.* have taken exception to the theoretical analysis of Ref. [4], suggesting they have not correctly handled the oblique corrections to G_F. He finds that the anomaly in the invisible width of the Z and the NuTeV result can be explained by invoking non-Standard Model mixing to a heavy singlet state and a heavy Higgs.[8]

	ν_μ	$\bar{\nu}_\mu$
CCFR	951000	170000
CDHS	638605	551390
$E_{\mathrm{hadronic}} > 25$ GeV	187688	13625
CCFR/CDHS	$\times 5.1$	$\times 12.5$

Table 1. Relative statistics of CCFR and CDHS data for determination of the strange and antistrange seas from dimuon production.

2. Shadowing and Nuclear Corrections

Miller and Thomas have suggested that because of VMD effects "there is a nuclear correction, arising from the higher-twist effects of nuclear shadowing, for which no allowance has been made in the NuTeV analysis. This correction may well be of the same size as the reported deviation."[9]. NuTeV has responded to this in Ref.[10] and we find this explanation to be without foundation. First, the mean NuTeV Q^2 is 25.6 GeV^2 for ν events and 15.4 GeV^2 for the $\bar{\nu}$ data. The models discussed by Miller and Thomas are at much lower Q^2 although the precise region is not stated. There appears to have been a misunderstanding about the NuTeV analysis as well. The original Miller and Thomas paper implies that both the Llewellyn Smith variables[11] R_ν and $R_{\bar{\nu}}$ increase and in fact their result *increases* the anomaly.[10] This has been acknowledged by Miller but the original paper has been neither retracted nor modified.[12] Our measured variables in the either ν or $\bar{\nu}$ sign-selected beam are close to the Llewellyn Smith quantities and hence the Miller-Thomas model's disagreements in R_ν and $R_{\bar{\nu}}$ are experimentally significant. It is worth noting that our Paschos-Wolfenstein based technique causes such effects to largely cancel the individual effects arising in the Llewellyn Smith relations.[2] Nonetheless NuTeV has attempted to include the effect of such models, but we can find none consistent with the data. Melnitchouk and Thomas [13] respond to our comment that VMD shadowing is not motivated by charged lepton DIS data in our kinematic region. The two-phase shadowing model they discuss is not the pure VMD model provided in Ref. [9]. The two models have very different Q^2 dependence in the region relevant for NuTeV. [10] We welcome the additional work in the new reference, but it does not address the effects on the NuTeV electroweak measurements. In general NuTeV is happy to take specific models and process them though the analysis chain to precisely and unambiguously determine the effects. We suggest this method since the external application of models to the NuTeV analysis can easily lead to errors in the conclusions.

S. Kumano has suggested the anomaly may be due to nuclear effects modifying

the Paschos-Wolfenstein relation.[15] We believe the shifts are not correctly averaged over x; the effects he discusses are at high x and low Q^2. This region is removed by our cut on hadronic energy and in any case is only a small fraction of the cross-section.

3. Neutrino Oscillations

Giunti and Laveder suggest the anomaly can be explained by neutrino oscillations from $\nu_e \rightarrow \nu_{\text{sterile}}$ at a $\Delta m^2 \sim$ 10–100 eV^2.[16] This model is ruled out within the analysis. The ν_e flux is determined in two ways. Our beam simulation uses the measured $K \rightarrow \mu\nu_\mu$ flux to predict $K \rightarrow \pi e \nu_e$ (and other ν_e sources.) We compare the prediction to an internal measurement from "short" showers, signaling the presence of an electromagnetic shower from the ν_e. The two are in excellent agreement as shown in Fig.3. On average for ν_e, $N_{\text{meas}}/N_{\text{pred}} = 1.05 \pm 0.03$, and for $\bar{\nu}_e$ we find 1.01 ± 0.04. Giunti and Laveder correctly determine that a $\approx 20\%$ shift in the ν_e flux is required, and therefore the explanation is ruled out at roughly 6σ.

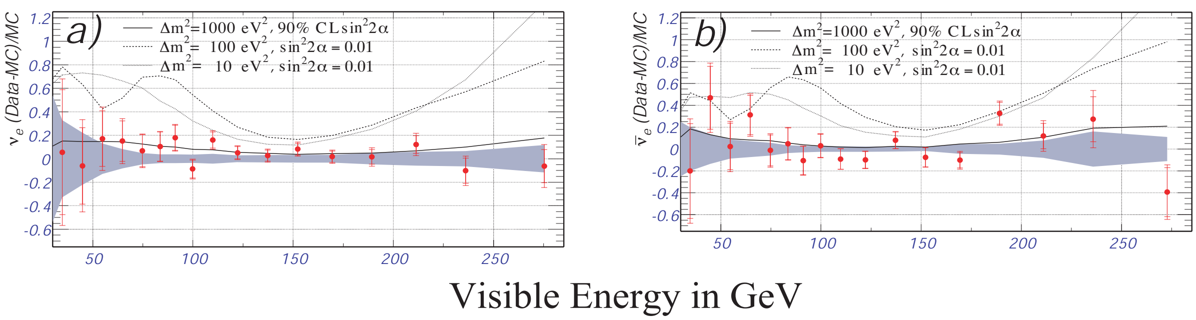

Figure 3. The ratio of the detected over predicted numbers of $(\nu_e, \bar{\nu}_e)$ events versus visible energy minus 1. The curves correspond to the predictions for $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$ oscillations with $\sin^2 2\theta = 0.01$, and Δm^2 of 100 and 1000 eV^2. The solid line is the 90% confidence upper limit for Δm^2=1000 eV^2. The shaded area corresponds to the systematic error band.

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